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CHEMICAL EVOLUTION OF THE GALACTIC DISK: EVIDENCE FOR A GRADIENT PERPENDICULAR TO THE GALACTIC PLANE

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ABSTRACT

An improved DDO abundance calibration presented in a previous paper is used to derive overall [Fe/H] abundances for 233 red giants in a sample of 63 open clusters with a wide range of ages. Membership of the giants in each cluster is confirmed by using velocity, astrometric, and photometric information. The newly derived abundances allow us: (1) to confirm the absence of a global age–metallicity relation for the entire open cluster sample; (2) to define a homogeneous abundance scale for the Galactic open cluster system. If this scale is adopted, a radial abundance gradient (∂[Fe/H]/$\partial R_{gc}=-0.07$ dex kpc^{-1}) as well as a steeper abundance gradient perpendicular to the Galactic plane (∂[Fe/H]/$\partial|Z|=-0.34$ dex kpc^{-1}) are found. Orbital motions for a subsample of 19 open clusters with sufficiently good distances and kinematical data are calculated by assuming a Miyamoto-type gravitational potential for the Galaxy. The dynamical evolution of each cluster is computed backwards for a time interval equal to its age and some relevant parameters of each cluster orbit are derived. It is found that both the radial and Z gradients determined from the observed cluster positions are very close to the paleogradient ones, namely, the gradients in metallicity of the gas out of which the clusters have been generated. © *1995 American Astronomical Society.*

1. INTRODUCTION

The chemical evolution of the different constituents of the Galaxy occurred on a rather different time scale. For instance, the metallic enrichment of the bulge was much faster than in the disk (Matteucci & Brocato 1990). During the evolution of the Galactic disk, nucleosynthesis in successive generations of stars proceeded along with the dynamical interaction of the stars and interstellar gas. As a consequence, surviving objects from those times constitute a fossil record of the state of the Galactic disk at various epochs of its evolution. Thus, the determination of chemical abundances of these objects has played an important role in the study of the major processes occurring during the disk evolution.

Numerous surveys along the Galactic plane have been used to investigate the existence and size of a galactic radial abundance gradient in the disk. A wide variety of objects have been used to determine this gradient, from H II regions (Shaver *et al.* 1983) or planetary nebulae (Pasquali & Perinotto 1993), through dF and dG stars (Edvardsson *et al.* 1993) and G and K giants (Neese & Yoss 1988) to open clusters (Geisler *et al.* 1992, hereafter referred to as GCM; Friel & Janes 1993, hereafter referred to as FJ, see references therein). Not all studies are in agreement as to the magnitude of the gradient, or even of its existence. In fact, depending on the method used considerable differences in the results have been obtained ranging from a zero radial metallicity gradient to a maximum value of -0.19 dex kpc^{-1} (e.g., see, Jennens & Helfer 1975; Peimbert *et al.* 1977). But there is general agreement for a gradient of ~ -0.07 dex kpc^{-1}.

On the other hand, there is considerable disagreement about whether there is a metallicity gradient perpendicular to the plane among field and/or open cluster stars of the Galactic disk population. While Yoshii *et al.* (1987) and Norris & Green (1989), for example, found clear evidence from stars within a few hundred parsecs of the Galactic plane for a composition gradient in the Z direction—in the sense that stars far off the plane are underabundant in heavy elements relative to the galactic plane ones—recent studies by GCM, FJ, and Carraro & Chiosi (1994a) did not detect any variation.

The primary aim of this paper is to provide a homogeneous body of accurate abundances for a large sample of open cluster giants in order to allow an improved examination of these gradients. The abundances for all these stars have been placed on the new DDO abundance scale derived by Piatti *et al.* (1993). We have paid particular attention to cluster membership by applying several criteria which virtually guarantee membership for our final open cluster sample.

In this paper we discuss the relationships between metallicity, position, and age of a large sample of open clusters, with the main purpose to put new constraints on any theory for the chemical evolution of the Galactic disk. In Sec. 2 we describe the selection of the sample, the assessment of cluster membership, and the derivation of reddening and metallicity. A discussion of the age-metallicity-position relation is presented in Sec. 3, together with the results of the orbital calculations for a subsample of 19 open clusters. Finally, a few concluding remarks are given in Sec. 4. We note that a preliminary version of the present results was presented by Piatti *et al.* (1995) but is superseded by the present paper.

2. THE SAMPLE SELECTION

2.1 *Photometric Data*

Galactic open clusters have long been used to improve our knowledge of the structure and early evolution of the Galactic disk. This is due to the relative ease in determining

TABLE 1. DDO photometry, reddening, and membership information sources of the studied clusters.

NAME	DDO Source	E(B-V) Source	Membership Criteria Vr	PM	Phot.
NGC 188	3, 9	10	11	12	
NGC 654	14		14	14, 15	14
NGC 659	14				14
NGC 752	14, 18, 29, 35, 36	51	52	14, 53, 54, 58	14
NGC 1342	18	19	20		7
NGC 1528	14		20		14
NGC 1545	14, 29	19	6, 20		14, 29
NGC 1647	14		14, 20		14
NGC 1662	18, 29	19	6, 20		
NGC 1807	21, 22	7, 19			7
NGC 1893	14				14
NGC 1907	14				14
NGC 2099	18	23			23
NGC 2158	18	24	25		7
NGC 2168	14	19	14	14	14
NGC 2186	14	26			14
NGC 2204	28	27	25		7
NGC 2232	30		6		30
NGC 2243	32	33	5, 34		31, 32
NGC 2251	14, 82	19			82
NGC 2264	30		20		30
NGC 2287	14, 37	37	6, 38, 39	133	14, 37
NGC 2301	40	41	6		40
NGC 2335	30	42	42		42
NGC 2343	30	43			43
NGC 2360	82, 90	5	116		82
NGC 2383	40				40
NGC 2420	45	46	5, 25, 47, 48	49, 50	
NGC 2421	14				14
NGC 2422	14			14	14
NGC 2423	40, 82	80	116		
NGC 2437	82	75			82
NGC 2451	3, 30		39	39	30
NGC 2467	14	19			7, 14
NGC 2477	2, 3, 4	5	6	1	7
NGC 2482	82, 91	91			82
NGC 2483	14				14
NGC 2489	82	19, 74	6		82
NGC 2506	55	55	5, 25, 56	57	
NGC 2516	40	41	6, 39	39	40
NGC 2527	30	59	6		30
NGC 2533	14		14		14
NGC 2539	62	61	63		62
NGC 2546	14, 30, 82	125	39		14, 30
NGC 2547	64	64			64
NGC 2548	30	61	39	39, 65	30
NGC 2567	30, 66	66			30, 66
NGC 2571	67				67
NGC 2632	18, 21, 29, 60, 130	77	39, 63	39	
NGC 2660	4	56	6		68
NGC 2669	40	69		70	40
NGC 2670	14		39		14
NGC 2682	3, 76	77	78	79	
NGC 2972	40	69			40
NGC 3033	40	40			40

TABLE 1. (continued)

NAME	DDO Source	E(B-V) Source	Membership Criteria		
			Vr	PM	Phot.
NGC 3114	14, 40	81	6, 39		14, 40
NGC 3228	82	135			82
NGC 3532	83	84, 85, 86	39	87, 88	83
NGC 3680	90, 91	10	5		90, 91
NGC 3960	92	92	5, 6		92
NGC 4349	94, 95	93			95
NGC 4609	40	96, 97			40
NGC 5138	98	98			98
NGC 5168	40				40
NGC 5281	40	100			40
NGC 5316	95	102	39		95
NGC 5460	103, 104		6		103
NGC 5617	40	105, 106, 107, 108	6		40
NGC 5662	109	109		110	109
NGC 5749	111				111
NGC 5822	40, 94, 114, 115	114	116		40, 115
NGC 5823	92, 94	92			7
NGC 6067	14, 40	117, 118	14, 39, 119		14, 40
NGC 6134	120	120	120		
NGC 6204	14				14
NGC 6208	82	82	6		82
NGC 6249	40				40
NGC 6259	82	19	6		82
NGC 6281	40	97, 123			40
NGC 6416	14		39		14
NGC 6425	82	82	6		82
NGC 6475	14	125	39		14
NGC 6494	95	97	6	126	95
NGC 6633	3, 82	134	63	72	82
NGC 6694	14				14
NGC 6755	14				14
NGC 6791	127	73, 128, 129	5, 129		7
NGC 6819	3				
NGC 7063	14				
NGC 7209	29	19	6	71	
NGC 7235	14				14
NGC 7510	14				14
NGC 7789	130, 132	131	5, 124	122	
IC 348	121				
IC 2581	113				
IC 2714	112	112	112		112
IC 4651	16	8, 13, 41			91
IC 4725	14, 113	125	39, 119	39	14
Cr 121	104, 113	125	39	39	
Cr 223	99				99
h and χ Per	14				
Haf 8	40	26			40
Har 5	40	100	6		40
Hyades	121	77	89	89	
Lo 807	82	17			82
Mel 66	94	5	5, 34		7
Pi 4	40	26			40
Ru 18	30	26			30
Ru 46	30, 40	44			30, 40
Ru 79	14	101	119		14
Ru 107	40				40
St 14	14, 113				14
Tr 27	113				
Tr 37	121				

TABLE 1. (continued)

References for Table 1.

(1) Eggen & Stoy 1961; (2) Hartwick et al. (1972); (3) Goodenough 1976; (4) Hesser & Smith 1987; (5) Friel & Janes 1993; (6) Mermilliod 1994; (7) our present analysis; (8) Eggen 1971; (9) McClure 1974; (10) Canterna et al. 1986; (11) Greenstein & Keenan 1964; (12) Upgren et al. 1972; (13) Anthony-Twarog et al. 1988; (14) Schmidt 1984; (15) Stone 1977; (16) Smith 1982; (17) Hidayat & Wiramihardja 1978; (18) Janes 1979; (19) Lyngå1987; (20) Glushkova & Rastorguev 1991; (21) Yoss 1977; (22) Yoss et al. 1981; (23) West 1967; (24) Arp & Cuffey 1962; (25) Friel 1989; (26) Moffat & Vogt 1975a; (27) Hawarden 1976; (28) Dawson 1981; (29) Clariá et al. 1995b; (30) Clariá 1985; (31) Hawarden 1975; (32) Norris & Hawarden 1978; (33) Bonifazi et al. 1990; (34) Gratton 1982; (35) Goodenough 1970; (36) Hardy 1979; (37) Feinstein et al. 1978; (38) Levato & Malaroda 1979; (39) Harris 1976; (40) Clariá et al. 1989; (41) Nissen 1988; (42) Clariá 1973; (43) Clariá 1972; (44) Vogt & Moffat 1972; (45) McClure et al. 1974; (46) Osborn 1975; (47) Liu & Janes 1987; (48) Cohen 1980; (49) van Altena & Jones 1970; (50) Cannon & Lloyd 1970; (51) Daniel et al. 1994; (52) Rebeirot 1970; (53) Platais 1991a; (54) Cannon 1968; (55) McClure et al. 1981; (56) Geisler et al. 1992; (57) Chiu & van Altena 1981; (58) Francic 1989; (59) Lindoff 1973; (60) Janes & McClure 1971; (61) Pesch 1961; (62) Clariá & Lapasset 1986a; (63) Mermilliod & Mayor 1989; (64) Clariá 1982; (65) Ebbighausen 1939; (66) Clariá & Lapasset 1986b; (67) Clariá 1976; (68) Hartwick & Hesser 1973; (69) Vogt & Moffat 1973; (70) King 1979; (71) Platais 1991b; (72) Sanders 1973; (73) Montgomery et al. 1994; (74) Ramsay & Pollacco 1992; (75) Cuffey 1941; (76) Janes & Smith 1984; (77) Canterna 1976; (78) Mathieu et al. 1986; (79) Girard et al. 1989; (80) Smith & Nandy 1962; (81) Schmitd 1982; (82) Clariá et al. 1995a; (83) Clariá & Lapasset 1988; (84) Wizinowich & Garrison 1982; (85) Schneider 1987; (86) Eggen 1981; (87) Koelbloed 1959; (88) King 1978a; (89) Schwan 1991; (90) McClure 1972; (91) Clariá & Lapasset 1983; (92) Janes 1981; (93) Lohmann 1961; (94) Dawson 1978; (95) Clariá & Lapasset 1989; (96) Feinstein & Marraco 1971; (97) Mermilliod 1981; (98) Clariá 1980; (99) Clariá & Lapasset 1991; (100) Moffat & Vogt 1973; (101) Walker 1987; (102) Pedreros 1987; (103) Clariá et al. 1993; (104) Clariá & Osborn 1976; (105) Haug 1978; (106) Kjeldsen & Frandsen 1991; (107) Lindoff 1968; (108) Moffat & Vogt 1975b; (109) Clariá et al. 1991; (110) King 1980; (111) Clariá & Lapasset 1992; (112) Clariá et al. 1994; (113) Dean 1981; (114) Twarog & Anthony-Twarog 1993; (115) Clariá & Lapasset 1985; (116) Mermilliod & Mayor 1990; (117) Thackeray et al. 1962; (118) Eggen 1983; (119) Mermilliod et al. 1987; (120) Clariá & Mermilliod 1992; (121) McClure 1976; (122) McNamara & Solomon 1981; (123) Feinstein & Forte 1974; (124) Stryker & Hrivnak 1984; (125) Becker & Fenkart 1971; (126) Sanders & Schröder 1980; (127) Janes 1984; (128) Harris & Canterna 1981; (129) Garnavich et al. 1994; (130) Janes 1976; (131) Küstner 1923; (132) Janes 1977; (133) Ianna et al. 1987; (134) Hiltner et al. 1958; (135) Hogg 1963.

their reddenings, distances, metallicities and ages with considerable precision (see, e.g., Janes *et al.* 1988).

After the pioneering investigation by Janes (1979), in which he compiled UBV and DDO photometric information for 41 open clusters, a steady increase in the quantity and quality of DDO data for open cluster stars has occurred. Therefore, the first criterion for selecting clusters has been the availability of reliable DDO photometric measurements.

In view of the efficiency of the DDO technique for deriving metallicities of Population I red giants, we have employed it in our analysis. In total, 621 red giant candidates with existing UBV–DDO photometry in 114 open clusters have been analyzed. A large portion of the photometric data comes from numerous papers published by several authors. A minor percentage arises from still unpublished cluster observations that we have carried out at Cerro Tololo Inter-American Observatory (CTIO, Chile), European Southern Observatory (ESO, Chile), Complejo Astronómico El Leoncito (Casleo, Argentina), Bosque Alegre Astrophysical Station (BAAS, Argentina), and Kitt Peak National Observatory (KPNO). The observational data together with an individual extensive analysis of these clusters will be published in forthcoming papers (Clariá *et al.* 1995a, 1995b). The cluster names and sources adopted here for the DDO colors are given in columns (1) and (2) of Table 1.

2.2 Membership Information

The separation of field stars from red cluster giants was carried out on the basis of radial velocity, proper motion, and/or photometric data. In particular, we were greatly helped by the radial velocity investigations by J. C. Mermilliod and collaborators using CORAVEL observations. In some clusters CORAVEL information has been available for the present study in advance of publication. These data provide velocities with an accuracy of typically $\sim$0.5 km/s and thus very definitive cluster membership status. We have also used other lower quality radial velocity membership data, when available.

Proper motions have been taken from a variety of sources, hence they are of somewhat heterogeneous origin and accuracy. However, since most of our cluster stars are brighter than $V\sim12$ mag (the limit of the photographic works lies typically around $V=20$ mag) and the spread of proper motions in a given cluster is generally very small, we have considered the proper motion membership probability as a high quality membership criterion.

In addition, we have used a third source of membership status based on combined UBV and DDO data and the photometric criteria described by Clariá & Lapasset (1983) and Schmidt (1984). A few stars in five clusters with published DDO photometry (NGC 1342, 1807, 2158, 2204, and 6791) have neither radial velocity nor proper motion nor photometric membership information. In these cases, cluster membership was examined by applying the photometric criteria described by Clariá & Lapasset (1983). These criteria were also used to evaluate cluster membership in 11 clusters with new UBV and DDO photometric data still not published by us (see Table 1). The latter membership classifications must be considered as preliminary.

Summing up, conclusive membership information exists virtually for our entire sample. Columns (4)–(6) of Table 1 give the radial velocity, proper motion, and photometric references used to assign the final membership status. In those few cases where there was disagreement about the membership status of a particular star, we assigned greatest weight to the highest quality source assessment. We note that, regardless of the membership status, we have eliminated stars whose $C(42-45)$ colors and/or MK spectral types suggest that they are objects either too early or too luminous (e.g., supergiants) for a DDO analysis.

Thus, a total of 31 clusters were removed from our original sample on the basis of their membership information as well as 12 clusters because their stars are not G/K giants. We have also discarded five clusters for other reasons: NGC 2477 and NGC 5662 because comprehensive studies by Hartwick *et al.* (1972) and Clariá *et al.* (1991) show evidences for differential reddening of up to 0.2 mag across these clusters. NGC 5823 does not resemble a coherent sample of giants and it is not clear whether the giants form a physical group (Dawson 1978); Tr 27 is affected by a strong selective absorption (Thé & Stokes 1970) which leads to a quite uncertain metallicity. Finally, Tr 37 was discarded because the only red giant with DDO data is a μ Cephei variable (Garrison & Kormendy 1976).

As a result of this first analysis the original sample was reduced to 66 clusters with confirmed red giants with a high degree of probability. This cluster sample nearly trebles that of FJ. However, the age range of the present cluster sample includes clusters generally younger than that of FJ, but generally older than 10^8 yr.

2.3 *Reddening*

Before any subsequent analysis based on DDO photometry, the reddening of the clusters must be known as accurately as possible. Although reddening uncertainties can influence the DDO metallicity determination, these uncertainties are not as critical for the DDO colors as they are for broadband photometry.

Fortunately, most of the clusters have been the subject of detailed investigations via UBV photometry. Therefore, we used the reddening values published by several authors, which in most cases represent reliable determinations as they involve a lot of stars and generally independent procedures. Column 3 of Table 1 gives the source from which the reddenings were taken. Clusters without an $E(B-V)$ source in Table 1 have either all their stars classified as nonmembers or they all lie outside the range of the DDO calibrations. For some clusters we have adopted the mean of the $E(B-V)$ color excesses given by different authors. In particular, we have assigned weights to the reddenings used in NGC 6791 and averaged the $E(B-V)$ determinations for 13 blue stars $[(B-V)\leq 0.15]$ in NGC 2482 (see Table 4 of Clariá & Lapasset 1983). Nissen's (1988) and Schmidt's (1982) $E(b-y)$ values for NGC 2301, NGC 2516, and NGC 3114 have been converted to $E(B-V)$ by using the relation $E(B-V)=1.351E(b-y)$ given by Crawford (1978). Four clusters (NGC 6134, 6208, 6425, and 7789) were dereddened by applying directly the method described by Janes (1977). Column 2 of Table 2 lists the adopted $E(B-V)$ values.

Once the $E(B-V)$ color excesses are known, the intrinsic *DDO* colors are determined using the color excess ratios given by McClure (1979). Whenever a star has two or more *DDO* references, the corresponding mean values were adopted.

2.4 *Metallicity*

Recently, Piatti *et al.* (1993) presented a revised *DDO* abundance calibration and described an iterative method for determining overall [Fe/H] abundances of Population I red giants. They have shown that this method yields abundances in very good agreement with those derived from high dispersion spectroscopy. They have also shown that the new [Fe/H] values of early G and late K giants are improved by approximately 0.1 dex with respect to those derived from the method of Janes (1975). We then decided to adopt for our analysis their calibration and procedure for determining metallicities.

Once we applied the above calibration to our 66 clusters, three of them (NGC 4609, 5281, and 5617) were found to contain giants whose DDO colors lie outside the range of the calibration. None of these stars will be considered in our subsequent analysis. In order to determine mean cluster metallicities, a few additional stars (eight in total) with very discrepant abundance indices were discarded. We have also eliminated star I−1 (Sandage 1962) in NGC 188, reported as a binary by Greenstein & Keenan (1964) and Spinrad & Taylor (1969); star 276 (Thackeray *et al.* 1962) in NGC 6067, classified as a double star by Mermilliod *et al.* (1987) and star 51 (Becker *et al.* 1976), whose orbit was derived by Mermilliod & Mayor (1990). We note that the inclusion or exclusion of spectroscopic binaries has no significant effect on the mean cluster abundance so that we have included them in our analysis in order to maximize the sample size.

Columns 3–8 of Table 2 give in succession the number N of cluster giants used to derive the DDO ΔCN index (Piatti *et al.* 1993), the mean value of ΔCN and its standard deviation, the derived cluster abundance and estimated uncertainty, and finally the average number of iterations performed till we obtained a convergence in the [Fe/H] values within 0.01 dex. A comparison of the present metallicities with those recently derived by Clariá *et al.* (1994) and Piatti *et al.* (1993) using the same technique, shows an excellent agreement. The small differences which are apparent in some clusters (e.g., IC 2714) are due to the large sample of giants here considered and/or to a better estimate of the mean reddening adopted in the present paper. A comparison of our metallicities with those of FJ for twelve clusters in common yields $\langle[\mathrm{Fe/H}]_{DDO}-[\mathrm{Fe/H}]_{\mathrm{FJ}}\rangle=0.07\pm0.10$. As given in Piatti *et al.* (1993) our typical abundance uncertainty is 0.10–0.20 dex per cluster.

TABLE 2. Mean cluster abundances.

NAME	E(B-V)	N	ΔCN	σ	[Fe/H]	σ	I
NGC 188	0.08	7	0.001	0.029	-0.16	0.11	2
NGC 752	0.035	7	-0.015	0.012	-0.22	0.05	2
NGC 1342	0.28	3	-0.022	0.031	-0.24	0.12	1
NGC 1545	0.36	1	-0.005		-0.18		1
NGC 1662	0.34	2	0.036	0.004	-0.03	0.01	1
NGC 2099	0.27	3	0.090	0.020	0.18	0.07	2
NGC 2158	0.43	3	-0.053	0.048	-0.36	0.18	1
NGC 2168	0.16	1	-0.031		-0.28		3
NGC 2204	0.08	5	-0.062	0.059	-0.39	0.22	2
NGC 2243	0.07	4	-0.130	0.033	-0.65	0.12	2
NGC 2251	0.20	3	-0.002	0.017	-0.17	0.06	3
NGC 2287	0.00	3	0.007	0.017	-0.13	0.06	2
NGC 2301	0.04	1	0.044		0.01		1
NGC 2335	0.40	1	0.047		0.02		1
NGC 2343	0.20	1	-0.062		-0.39		3
NGC 2360	0.09	10	0.005	0.018	-0.14	0.07	2
NGC 2420	0.02	8	-0.072	0.027	-0.43	0.10	2
NGC 2423	0.13	7	0.072	0.011	0.11	0.04	2
NGC 2437	0.20	1	0.061		0.07		1
NGC 2482	0.09	3	0.076	0.010	0.13	0.04	1
NGC 2489	0.40	1	0.068		0.10		2
NGC 2506	0.05	4	-0.084	0.023	-0.48	0.08	1.5
NGC 2516	0.11	1	0.049		0.02		2
NGC 2527	0.10	1	0.020		-0.09		0
NGC 2539	0.10	3	0.088	0.022	0.17	0.08	1
NGC 2546	0.11	1	0.005		-0.14		3
NGC 2547	0.06	1	-0.014		-0.21		1
NGC 2548	0.04	2	0.046	0.005	0.01	0.02	2.5
NGC 2567	0.13	2	0.019	0.050	-0.09	0.19	1
NGC 2632	0.00	3	0.093	0.017	0.19	0.06	1
NGC 2660	0.37	5	-0.030	0.035	-0.27	0.13	2
NGC 2682	0.06	14	0.039	0.030	-0.01	0.11	2
NGC 2972	0.35	2	0.017	0.002	-0.09	0.01	1
NGC 3114	0.08	4	0.006	0.037	-0.14	0.14	2
NGC 3532	0.03	3	0.017	0.025	-0.10	0.09	2
NGC 3680	0.06	8	-0.001	0.019	-0.16	0.07	2
NGC 3960	0.29	3	0.027	0.012	-0.06	0.05	1
NGC 4349	0.33	5	0.009	0.009	-0.12	0.04	1
NGC 5138	0.25	1	0.092		0.18		1
NGC 5316	0.34	2	0.038	0.032	-0.02	0.12	1
NGC 5822	0.15	13	0.050	0.023	0.03	0.09	2
NGC 6067	0.35	3	0.040	0.019	-0.01	0.07	1
NGC 6134	0.35	7	0.097	0.028	0.20	0.10	2
NGC 6208	0.32	3	0.035	0.016	-0.03	0.06	2
NGC 6259	0.65	2	0.045	0.023	0.01	0.09	1.5
NGC 6281	0.15	2	0.044	0.033	0.00	0.12	1.5
NGC 6425	0.27	1	0.066		0.09		1
NGC 6475	0.04	1	0.051		0.03		1
NGC 6494	0.39	2	0.077	0.040	0.13	0.15	2
NGC 6633	0.17	3	0.037	0.014	-0.02	0.05	2
NGC 6791	0.13	6	0.043	0.036	0.00	0.14	1
NGC 7209	0.15	1	0.011		-0.12		1
NGC 7789	0.24	17	-0.023	0.036	-0.24	0.13	2
IC 2714	0.36	5	0.046	0.028	0.01	0.10	2
IC 4651	0.11	8	0.065	0.023	0.08	0.09	1
Haf 8	0.36	2	0.058	0.017	0.06	0.06	2
Har 5	0.17	1	-0.022		-0.24		1
Hyades	0.00	4	0.094	0.007	0.19	0.03	2
Lo 807	0.24	1	-0.016		-0.22		2
Mel 66	0.14	6	-0.074	0.024	-0.44	0.09	1
Pi 4	0.03	2	-0.012	0.022	-0.20	0.08	1
Ru 18	0.67	1	0.065		0.08		2
Ru 46	0.07	2	0.008	0.049	-0.13	0.18	1.5

3. ANALYSIS AND DISCUSSION

3.1 Introduction

As is well known, the open clusters define a system, the study of which is important for the knowledge of the structure and early evolution of the Galactic disk. In fact, the old open clusters provide information about the star formation in the early evolutionary phases of the Galactic disk. Intermediate-age open clusters have proven to be good discriminators between standard evolutionary models and those computed including convective overshooting (see, e.g., Mazzei & Pigato 1988; Aparicio *et al.* 1990; Clariá *et al.* 1994), while young open clusters, specially those associated with H II regions or with ages of the order of 10^7 yr or less, have been used to trace the spiral structure in the Galactic disk.

3.2 Age–Metallicity–Position Relation

We can now address the question of the existence of a general relation between metallicity, age, and Galactic position, by examining probably the largest open cluster sample yet analyzed, with abundances derived on a homogeneous scale. The behavior of these three variables as well as their relationships should reflect the chemical evolution of the Galactic disk.

We have extracted from Lyngå's (1987) catalogue the galactic longitudes and latitudes, distances from the Sun, and ages of nearly all clusters listed in our Table 2. In addition, we have adopted the parameters given by FJ for 12 clusters in common with the present study and used those derived by Clariá *et al.* (1994) for IC 2714. The basic data for Lodén 807, not included in Lynga's catalogue, were taken from Hidayat & Wiramihardja (1978). Unfortunately, these authors did not estimate the age of Lodén 807 so that we could not use it in the age–metallicity relation (AMR) analysis.

We have calculated for each cluster the galactocentric coordinates (X,Y,Z), the galactocentric distance R_{gc} (using $R_{gc\odot}=8.5$ kpc), and the distance $r=(X^2+Y^2)^{1/2}$ projected on the Galactic plane. Table 3 lists these basic properties together with the galactic coordinates and the adopted distances and cluster ages. We have excluded NGC 2343 from Table 3 because it has only one red giant with a quite uncertain *DDO* abundance.

In the scenario of the galactic chemical evolution, the iron-to-hydrogen ratio may in principle be expressed as

$$[\mathrm{Fe/H}]=F(R_{gc},Z,\mathrm{Age}).$$

Therefore, if we want to examine how the metallicity varies as a function of one of these three variables, we should first correct the dependence the metallicity could have on the other two variables. This correction is fundamental since if we neglect it, the relation between metallicity and the regarded variable could include spurious effects. Janes (1979), for example, obtained first a quantitative estimate of the overall $|Z|$ dependence of the δCN abundance index from an analysis of a sample of stars at the North Galactic pole. He found that a slope of -0.05 ± 0.01 mag kpc^{-1} gives a satisfactory description of the $|Z|$ dependence on δCN and added this correction factor to his combined field and cluster data. Then, he used the normalized [Fe/H] values to derive a radial abundance gradient, wherein the $|Z|$ dependence should have been eliminated. However, this would be strictly correct only if the star sample in the direction of the North Galactic pole is not age-metallicity dependent. This certainly seems to be the case according to the results obtained in some recently comprehensive studies (see, e.g., GCM, FJ, Edvardsson *et al.* 1993).

A similar treatment was performed by FJ to investigate the metallicity gradient perpendicular to the Galactic plane from spectroscopic abundances of 24 open clusters. These authors found no trend of [Fe/H] values with the height Z above the Galactic plane, once the effect of radial abundance gradient was accounted for and all metallicities were normalized to those the clusters would have if they were moved to the solar galactocentric distance. However, as discussed below, this result may be biased by an age selection effect, in the sense that the metallicities of old open clusters used by FJ do not show a correlation with Z. Even more,if this were not true, then the radial abundance gradient derived by FJ would be contaminated by the Z distribution of their cluster sample. GCM, using Washington photometry of a larger sample of open clusters (35) than that of FJ, found a somewhat steeper radial abundance gradient. These considerations can also be applied to the study of Carraro & Chiosi (1994b), which is based on the spectroscopic and photometric metallicity scales of FJ and GCM, respectively.

We have preferred to do a linear least-squares fit of the abundances simultaneously as a function of R_{gc}, Z, and Age, weighting the mean abundance in each cluster by the number of red giants used in its determination. We have discarded NGC 6791 because it had by far the largest residual, principally in the [Fe/H]-$|Z|$ plane (see Sec. 3.3). The relation obtained connecting the age, the metallicity, and the position on the disk is the following:

$$[\mathrm{Fe/H}]=0.58(\pm0.12)-0.07(\pm0.01)\cdot R_{gc}-0.34 \times(\pm0.03)\cdot|Z|-0.0002(\pm0.0005)\cdot \mathrm{Age} \quad (1)$$

with a standard weighted deviation of ±0.13 dex. R_{gc} and $|Z|$ are given in kpc while the Age is expressed in units of 10^8 yr. We have tried to compute another kind of fitting by employing n degree polynomes and/or exponential functions, but none of them satisfactorily fit the data. In Eq. (1) each coefficient accompanying the respective variable represents the intrinsic slope between the metallicity and that variable or, in other words, they show a radial and Z abundance gradient of -0.07 and -0.34 dex kpc^{-1}, respectively, and the absence of a global age–metallicity relation for our open cluster sample. The zero point (0.58 dex) in Eq. (1) should not be considered as the [Fe/H] of an object located at the Galactic center that was born recently. This is because a comparison of bulge with disk G/K giants may be inappropriate and a steady trend from one component to the other is not necessarily expected. Furthermore, if the radial abundance gradient seen in the solar neighborhood is extended to the bulge, then average disk stars at the edge of the bulge will have [Fe/H]~0.6 dex, which is significantly larger than the mean value (-0.25 dex) found recently by McWilliam &

TABLE 3. Basic cluster properties.

NAME	ℓ	b	d (kpc)	Z (kpc)	r (kpc)	R_{gc} (kpc)	Age ($\times10^8$ yrs.)	[Fe/H]
NGC 188	122.78	22.46	1.55	0.59	9.35	9.37	50.0	-0.16
NGC 752	137.17	-23.17	0.40	-0.16	8.77	8.78	24.0	-0.22
NGC 1342	154.99	-15.38	0.55	-0.15	8.98	8.99	3.0	-0.24
NGC 1545	153.36	0.17	0.80	0.00	9.22	9.22	1.9	-0.18
NGC 1662	187.70	-21.12	0.40	-0.14	8.87	8.87	3.0	-0.03
NGC 2099	177.65	3.09	1.35	0.07	9.85	9.85	3.0	0.18
NGC 2158	186.64	1.76	4.90	0.15	13.38	13.38	11.0	-0.36
NGC 2168	186.58	2.18	0.87	0.03	9.36	9.36	1.1	-0.28
NGC 2204	226.01	-16.07	3.10	-0.86	10.78	10.82	30.2	-0.39
NGC 2243	239.50	-17.97	4.10	-1.27	11.01	11.08	50.0	-0.65
NGC 2251	203.60	0.13	1.55	0.00	9.94	9.94	3.0	-0.17
NGC 2287	231.10	-10.23	0.74	-0.13	8.98	8.98	1.0	-0.13
NGC 2301	212.55	0.28	0.75	0.00	9.14	9.14	1.1	0.01
NGC 2335	223.62	-1.27	1.00	-0.02	9.25	9.25	1.6	0.02
NGC 2360	229.80	-1.42	1.20	-0.03	9.32	9.32	19.0	-0.14
NGC 2420	198.11	19.65	1.90	0.64	10.22	10.24	40.0	-0.43
NGC 2423	230.47	3.55	0.87	0.05	9.08	9.08	3.5	0.11
NGC 2437	231.87	4.07	1.41	0.10	9.43	9.43	3.0	0.07
NGC 2482	241.63	1.97	0.80	0.03	8.91	8.91	4.0	0.13
NGC 2489	246.71	-0.78	1.20	-0.02	9.04	9.04	2.4	0.10
NGC 2506	230.57	9.91	2.70	0.47	10.39	10.41	40.0	-0.48
NGC 2516	273.94	-15.88	0.44	-0.12	8.48	8.48	1.1	0.02
NGC 2527	246.13	1.89	0.60	0.02	8.76	8.76	10.0	-0.09
NGC 2539	233.73	11.12	1.28	0.25	9.30	9.30	6.6	0.17
NGC 2546	254.90	-1.98	1.00	-0.04	8.81	8.81	0.4	-0.14
NGC 2547	264.55	-8.55	0.40	-0.06	8.55	8.55	0.6	-0.21
NGC 2548	227.92	15.37	0.61	0.16	8.91	8.91	3.0	0.01
NGC 2567	249.81	2.98	1.70	0.09	9.23	9.23	0.7	-0.09
NGC 2632	205.54	32.52	0.18	0.10	8.64	8.64	6.6	0.19
NGC 2660	265.86	-3.03	2.10	-0.11	8.90	8.90	15.8	-0.27
NGC 2682	215.58	31.72	0.80	0.42	9.06	9.07	50.0	-0.01
NGC 2972	274.69	1.77	1.20	0.04	8.49	8.49	1.0	-0.09
NGC 3114	283.34	-3.83	0.90	-0.06	8.34	8.34	1.1	-0.14
NGC 3532	289.64	1.46	0.50	0.01	8.35	8.35	3.5	-0.10
NGC 3680	286.77	16.93	0.80	0.23	8.31	8.32	40.0	-0.16
NGC 3960	294.41	6.18	1.66	0.18	7.96	7.96	10.0	-0.06
NGC 4349	299.77	0.82	1.70	0.02	7.80	7.80	2.2	-0.12
NGC 5138	307.55	3.55	1.80	0.11	7.54	7.54	1.5	0.18
NGC 5316	310.23	0.12	1.12	0.00	7.82	7.82	1.9	-0.02
NGC 5822	321.71	3.58	0.74	0.05	7.93	7.93	12.0	0.03
NGC 6067	329.76	-2.20	2.10	-0.08	6.77	6.77	0.8	-0.01
NGC 6134	334.92	-0.19	0.79	0.00	7.79	7.79	6.3	0.20
NGC 6208	333.69	-5.82	1.00	-0.10	7.62	7.62	10.0	0.03
NGC 6259	341.98	-1.52	0.77	-0.02	7.77	7.77	2.2	0.01
NGC 6281	347.82	2.01	0.60	0.02	7.92	7.92	2.2	0.00
NGC 6425	357.97	-1.60	0.80	-0.02	7.70	7.70	0.6	0.09
NGC 6475	355.86	-4.53	0.24	-0.02	8.26	8.26	2.2	0.03
NGC 6494	9.85	2.85	0.66	0.03	7.85	7.85	2.2	0.13
NGC 6633	36.09	8.28	0.32	0.05	8.25	8.25	6.6	-0.02
NGC 6791	70.01	10.96	5.30	1.01	8.31	8.37	80.0	0.00
NGC 7209	95.51	-7.34	0.90	-0.12	8.63	8.63	3.0	-0.12
NGC 7789	115.49	-5.36	1.80	-0.17	9.41	9.41	20.0	-0.24
IC 2714	292.44	-1.76	1.32	-0.04	8.09	8.09	3.2	0.01
IC 4651	340.07	-7.88	0.71	-0.10	7.84	7.84	24.0	0.08
Haf 8	227.52	1.34	1.70	0.04	9.73	9.73	5.0	0.06
Har 5	299.96	1.97	1.03	0.04	8.03	8.03	0.4	-0.24
Hyades	180.05	-22.40	0.05	-0.02	8.54	8.54	6.6	0.19
Lo 807	306.79	0.20	0.68	0.00	8.11	8.11		-0.22
Mel 66	259.61	-14.29	2.90	-0.72	9.42	9.45	50.0	-0.44
Pi 4	262.74	-2.37	0.60	-0.03	8.60	8.60	0.2	-0.20
Ru 18	239.94	-4.92	1.03	-0.09	9.06	9.06	1.3	0.08
Ru 46	238.37	5.89	0.75	0.08	8.91	8.91	31.6	-0.13

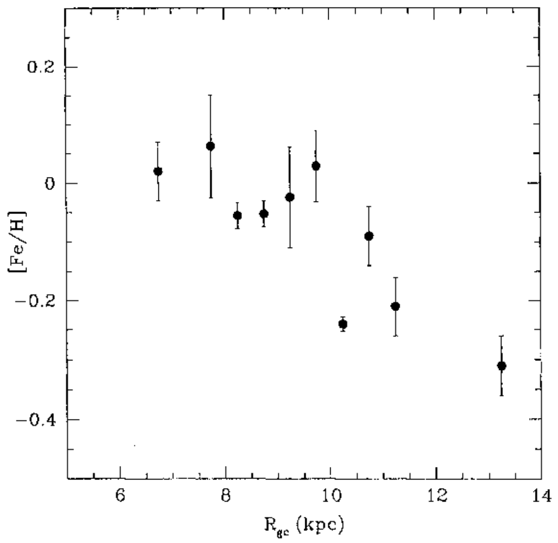

FIG. 1. The radial abundance gradient across the Galactic disk derived from the clusters of Table 2. Filled circles and bars denote mean abundance and standard deviation, respectively, for clusters within a specific interval in R_{gc}. The data have been corrected for the Z-dependence on metallicity.

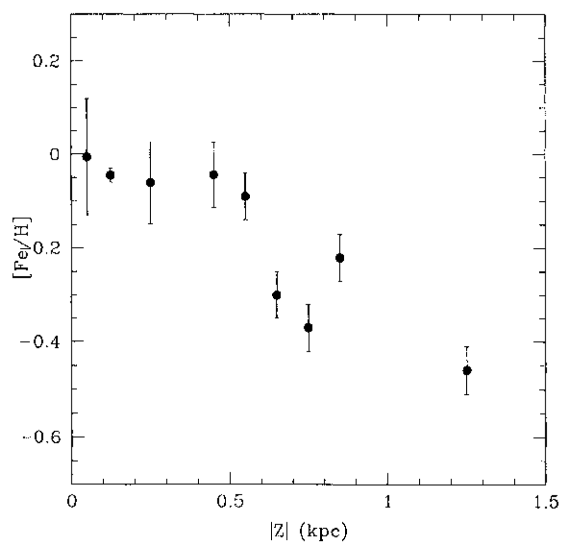

FIG. 2. The Z abundance gradient for the same clusters as in Fig. 1, corrected for the effect of the radial gradient as discussed in the text. Filled circles and bars represent mean abundance and standard deviation, respectively, for clusters within a specific interval in Z.

Rich (1994) from an analysis of echelle spectra of bulge K giants.

The metallicity of each cluster must be appropriately corrected if we want to examine its relation to any of the three variables independently of the other two. Thus, if i,j,k denote any possible assignment for R_{gc}, $|Z|$, and Age, then the corrected [Fe/H] value as a function of the variable i is expressed by

$$[\mathrm{Fe/H}]_i=[\mathrm{Fe/H}]_{\mathrm{measured}}-\frac{\partial[\mathrm{Fe/H}]}{\partial j}\cdot\Delta j-\frac{\partial[\mathrm{Fe/H}]}{\partial k}\cdot\Delta k, \tag{2}$$

which is a generalization of Eq. (4) of Carraro & Chiosi (1994b).

Figure 1 illustrates the actual behavior of the metallicities with respect to galactocentric distance. The points in Fig. 1 represent the average of corrected [Fe/H] values in a specific interval of R_{gc}, weighted by the number of giants in each cluster. The size of the bins was chosen to have a representative subsample of clusters in each bin along R_{gc}. A similar treatment was performed to obtain Fig. 2, wherein the behavior of [Fe/H] with Z is shown. We note that the metallicity of each cluster in both figures has been corrected to the value it would have if located on the Galactic plane (Fig. 1) or at the solar galactocentrinc distance (Fig. 2), respectively.

Our radial abundance gradient is in very good agreement with the values from many independent studies both of metallicities in the interstellar medium (see, e.g., Pagel *et al.* 1992) and other samples of clusters (e.g., Grenon 1987; GCM; FJ; Carraro & Chiosi 1994b). We have obtained, however, a somewhat controversial result with respect to the existence of a vertical gradient. In fact, our open cluster sample clearly demonstrates the existence of a well-defined abundance gradient perpendicular to the Galactic plane. Many authors have previously found evidence for such a gradient, although the values in some cases appear to be quite discrepant. For example, using *DDO* photometry of late-type giants in the direction of both galactic poles, several authors found a vertical gradient ranging from approximately -0.20 to -0.40 dex kpc^{-1} (see, e.g., Hartkopf & Yoss 1982; Yoss *et al.* 1987; Norris & Green 1989, and references therein). Other independent studies have also shown evidence for a significant vertical gradient: Trefzger *et al.* (1985) using Walraven photometry of F and G stars found -0.60 dex kpc^{-1}, while Yoshii *et al.* (1987) derived -0.50 dex kpc^{-1} from *UBV* star-count data for a large sample of stars in the direction to the North Galactic pole.

Recent work has used different open cluster datasets instead of field stars to determine chemical composition gradients in and perpendicular to the disk. Cameron (1985) used metallicities determined from *UBV* photometry and found no gradient perpendicular to the plane. However, the number of clusters (38) used by Cameron is only about half the size of our sample. Secondly, his metallicities were derived from the normalized ultraviolet excess $\delta(U-B)_{0.6}$ index, which is less sensitive to changes in [Fe/H] than the DDO ΔCN index. In fact, a change in [Fe/H] from 0.0 to -0.75 causes a variation of $\sim$0.10 dex in $\delta(U-B)_{0.6}$ and $\sim$0.22 dex in ΔCN. Besides, Cameron's $\delta(U-B)_{0.6}$ calibration is valid up to [Fe/H] $\sim$0.0 and therefore metal-rich open clusters either fall outside this calibration or have underestimated abundances.

FJ have also suggested the absence of a Z abundance gradient from their study of 24 open clusters with ages greater than about 1 Gyr. A comparison of our metallicities with those of FJ for the 12 clusters in common yields $\langle[\mathrm{Fe/H}]_{DDO}-[\mathrm{FE/H}]_{\mathrm{FJ}}\rangle=0.07\pm0.10$. Without regarding the sign, the mean difference and standard deviation are 0.10 and 0.09, respectively. This comparison demonstrates that the agreement is reasonably good, but that up to a $\sim$0.1 dex difference may exist between the two metallicity scales. We conclude that the discrepancy in the Z gradient cannot be due to the abundance scales.

If the present open cluster sample is compared with that of FJ, two important differences appear to be evident. In fact, from the quantitative point of view our sample is 2.6 times larger than FJ's, whereas qualitatively only 30% of our clusters are older than 1 Gyr in contrast with almost the totality of clusters selected by FJ. Therefore, we believe that our open cluster sample is probably more representative of the Galactic disk system than that of FJ. Moreover, since their radial gradient (-0.09 ± 0.02 dex kpc^{-1}) derived from a much more extended range in galactocentric distance, is very similar to our determination, we believe that not only has there been little change in the radial gradient over time, but also that the FJ's sample includes clusters whose present Z distribution practically does not affect the dependence of the metallicity on R_{gc}. It is possible that the old open clusters had travelled many times from one side to another through the Galactic plane and now we are observing them at different heights out of the plane with respect to the Z values from birth (see Sec. *3.3*).

The existence of an AMR for the Galactic open cluster system has been debated for a long time with contrasting results (see, e.g., Janes *et al.* 1988). Both GCM and FJ concluded that open clusters do not show a pronounced global correlation between age and metallicity. The same result has been recently found by Carraro & Chiosi (1994b). We present in Fig. 3 the correlation of age with the metallicity of each cluster corrected for the effects of both the radial and Z gradients. For comparison purposes, we have also plotted in Fig. 3 the AMR for solar neighborhood field stars derived by Twarog (1980). Although the clusters selected in this study have ages within a more limited range in comparison to those of FJ or Twarog's F dwarfs, it seems again clear that there is no trend of metallicity with age, the scatter in Fig. 3 being particularly large for the youngest clusters. If only the clusters older than about 1 Gyr are considered, then our AMR shows better agreement with the Twarog relation than both the GCM and FJ AMRs. It is therefore tempting to conclude that the chemical evolution of these two disk components could not have been significantly different, at least during the last 6 Gyr.

In recent years, the presence of an intermediate thick-disk zone was suggested (Gilmore & Wyse 1986). The existence of a Galactic thick disk has been revealed by both high proper motion star surveys and high-z *in situ* star observations (e.g., Gilmore & Reid 1983; Sandage & Fouts 1987), which have indicated the existence of a number of stars with kinematics and abundances intermediate between the extreme halo and young disk values. Furthermore, Gilmore *et al.* (1995) have presented confirmatory evidence that the thick disk is predominantly composed of stars that are as old as the oldest disk stars, and possibly as old as the metal-rich globular clusters. They have also determined the thick disk iron abundance distribution from an in situ sample of F/G stars located beyond 1 kpc from the Galactic plane. The derived chemical abundance distribution is consistent with no vertical metallicity gradient in the thick disk, and with an

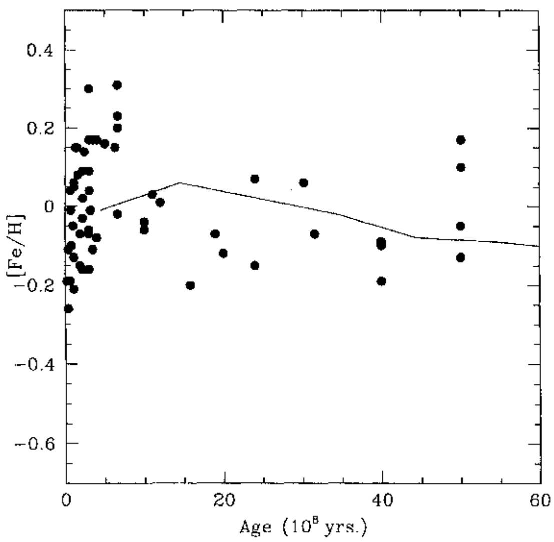

FIG. 3. The age–metallicity relation (AMR) for the clusters of Tables 2 and 3, after correction for both the Z and radial abundance gradients. The solid line represents the AMR for solar neighborhood disk field stars from Twarog (1980).

iron abundance distribution that has a peak at -0.7 dex. Then, if we consider the three distinguishable components of our Galaxy (halo, thick disk, and thin disk) and the ranges in metallicity, height and age of the present open cluster sample, we conclude that our results are related to the thin disk evolution rather than that of the thick disk population.

3.3 Galactic Orbits of Open Clusters

The knowledge of the dynamic behavior of the open clusters, especially those with ages greater than 1 Gyr, is an important tool to investigate whether there exists any similarity between the present abundance gradients across the Galactic disk and the so-called paleogradients, namely, the gradients in metallicity of the gas out of which the clusters were generated. The cluster abundances provide information about spatial variations in the production of chemical elements as well as about their chemical evolution with time. The old clusters are presently observed at galactocentric distances which are often different from those at the time of their birth. Since this could be due to their initial space motions, we have made an effort to reconstruct back in time these motions as accurately as possible.

Although it would seem rather difficult to determine the precise birthplaces of the clusters due to our ignorance of the physical processes that affected their dynamics, we may attempt to estimate an upper limit to the height out of the Galactic plane each cluster would have achieved during its life and investigate, in this situation, if a Z abundance gradient still exists. Note that if the orbit was not conservative, the maximum height out of the plane would be less than computed in our model.

In order to derive space motions some basic cluster parameters such as distances to the Sun, proper motions, and radial velocities are needed. As far as we know, sufficiently good distances and kinematical data are presently available

TABLE 4. Radial velocities, absolute proper motions, and space velocities of open clusters.

NAME	Vr (km/sec)	Ref.	μ_x ("/yr)	μ_y ("/yr)	Ref.	U (km/sec)	V (km/sec)	W (km/sec)
NGC 188	-47.40 ± 8.10	1	-0.00065	-0.00398	24	-22.71	-24.29	-44.93
NGC 752	7.96 ± 4.84	2, 3, 4	0.00333	-0.01580	25	7.25	-12.71	-28.00
NGC 1342	-10.87 ± 0.25	5	0.02450	0.00950	25	19.99	-31.46	58.50
NGC 2099	7.99 ± 1.08	5	0.00253	-0.00100	25	7.96	-13.47	11.04
NGC 2168	-8.3 ± 7.70	6	-0.01090	-0.01100	25	-7.94	-16.84	-61.65
NGC 2287	23.21 ± 1.98	5, 7, 8	-0.02300	-0.00300	26	25.44	8.82	-80.21
NGC 2420	72.99 ± 5.32	9, 10, 11, 12, 13	-0.00240	-0.00060	27	73.40	-20.53	3.80
NGC 2506	97.28 ± 10.50	9	-0.00010	0.00010	28	62.27	-72.96	16.30
NGC 2516	21.84 ± 2.87	14	0.00420	0.00420	25	1.93	-24.44	5.42
NGC 2548	8.90 ± 0.16	3	-0.01940	0.00100	25	37.03	5.13	-42.85
NGC 2632	34.41 ± 0.50	15	-0.03368	-0.01611	25	41.20	-23.03	6.76
NGC 2682	33.60 ± 0.62	16	-0.00790	-0.00730	29	32.60	-38.65	22.60
NGC 3114	1.93 ± 4.45	17	-0.00978	-0.0105	25	7.18	0.49	-60.82
NGC 3532	2.73 ± 5.46	17	-0.01096	0.01400	25	34.01	-14.48	20.41
NGC 5822	-29.74 ± 0.19	18	-0.02372	0.00900	25	62.18	-24.00	66.04
NGC 6475	-7.98 ± 3.98	19, 20, 21	-0.00390	-0.0056	30	8.45	-7.15	1.22
NGC 6633	-29.10 ± 0.30	15	0.00000	0.00317	25	26.05	-13.68	-2.04
NGC 7789	-55.36 ± 7.60	4, 22	0.01329	0.0136	25, 31	101.95	-100.39	94.41
Hyades	39.45 ± 0.35	23	0.10899	-0.0285	25	42.39	-20.76	-1.15

References for Table 4.

(1) Greenstein & Keenan 1964; (2) Hintzen et al. 1974; (3) Wallerstein et al. 1963; (4) Friel & Janes 1989; (5) Glushkova & Rastorguev 1991; (6) Petrie & Pearce 1961; (7) Liu et al. 1989; (8) Liu et al. 1991; (9) Cameron & Reid 1987; (10) Cohen 1980; (11) Smith & Suntzeff 1987; (12) Liu & Janes 1987; (13) Friel et al. 1989; (14) Evans et al. 1961; (15) Mermilliod & Mayor 1989; (16) Mathieu et al. 1986; (17) Harris 1976; (18) Mermilliod & Mayor 1990; (19) Buscombe & Kennedy 1968; (20) Abt et al. 1970; (21) Conti & van den Heuvel 1970; (22) Stryker & Hrivnak 1984; (23) Schwan 1991; (24) Upgren et al. 1972; (25) SAO Star Catalogue 1966; (26) Ianna et al. 1987; (27) Cannon & Lloyd 1970; (28) Carraro & Chiosi 1994a; (29) Murray et al. 1965; (30) Constantine et al. 1969; (31) McNamara & Solomon 1981.

only for the 19 open clusters listed in Table 4. Moreover, since these data come from a variety of sources, they are of a somewhat heterogeneous accuracy.

Mean cluster radial velocities and absolute proper motions were obtained averaging individual measurements from confirmed cluster giants. In eight clusters where giants have either no radial velocity or no absolute proper motion measurements, bright early-type stars with proper motion membership probabilities higher than 80% were used to derive the above mean values. These eight clusters and the corresponding relative proper motion studies used to confirm cluster membership are: NGC 2099 (Upgren 1966), NGC 2168 (Cudworth 1971), NGC 2506 (Chiu & van Altena 1981), NGC 2516 (King 1978a), NGC 2632 (Jones & Cudworth 1983), NGC 3532 (King 1978b), NGC 6475 (Constantine *et al.* 1969), and NGC 7789 (McNamara & Solomon 1981). Columns 2–9 of Table 4 list the computed mean radial velocities and x and y components of the absolute proper motions ($\mu_\alpha \cos \delta$ and μ_δ, respectively) for the subset of 19 clusters, together with the references of the original sources and the computed space motion components U (positive toward the Galactic anticenter), V, and W, all these referred to the Sun. The corrections applied to the observed velocities for the solar motion were $(-10, +6, +6)$ km s^{-1} in (U,V,W), and the solar galactocentric distance and circular velocity were taken to be 8.5 kpc and 226 km s^{-1}, respectively.

To represent the mass distribution of the Galaxy, we have adopted the Miyamoto & Nagai (1975) Galactic potential, which is axisymmetric and time invariant. In this model, the mass distribution of the Galaxy is described as a two component system: a spherical central and a flattened disk-like system. One can represent the gravitational potential of the three components of the Galaxy (bulge, disk, and halo) as the sum of two potential terms in the following form:

$$\Phi(R,Z) = -\sum_{i=1}^{2} G\mathcal{M}_i / \{R^2 + [a_i + (Z^2 + b_i^2)^{1/2}]^2\}^{1/2},$$

where $\mathcal{M}_i$ is the mass of the ith component, a_i the scale length of the disk-like system, b_i the scale of the spherical system, and G the gravitational constant. Assuming rotational equilibrium, it is possible to derive the corresponding circular velocity in the plane $V_c^2 = \partial\Phi/\partial R$ and fit the rotational curve in order to obtain the model parameters. By applying this procedure, Miyamoto *et al.* (1980) obtained the following values for the Galaxy potential: $a_1=0$, $a_2=7.283$ kpc, $b_1=b_2=0.495$, $M_1=0.295\times10^{11}$ $\mathcal{M}_\odot$, and $M_2=2.547\times10^{11}$ $\mathcal{M}_\odot$.

Using the above parameters, the equation of motion of a cluster in this potential is solved by numerical integration employing a code developed and kindly provided by S. Aarseth. We have computed the dynamical behavior of each cluster backwards for a time interval equal to its age, starting from the actual positions and velocities. In all cases the time step was chosen to allow a relative energy conservation better than 10^{-7}. From this evolution, we have taken the maximum value of the height out of the Galactic plane $|Z_{\max}|$, and

TABLE 5. Orbital parameters of open clusters.

NAME	R_p (kpc)	R_a (kpc)	$\|Z_{max}\|$ (kpc)	$\|Z\|$ (kpc)
NGC 188	6.41	9.37	0.78	0.59
NGC 752	6.32	8.71	0.27	0.16
NGC 1342	5.71	9.01	0.75	0.15
NGC 2099	7.02	9.85	0.19	0.07
NGC 2168	6.58	9.45	0.62	0.03
NGC 2287	7.95	8.97	0.87	0.13
NGC 2420	6.86	10.83	0.67	0.64
NGC 2506	4.82	10.45	0.55	0.47
NGC 2516	5.60	8.54	0.20	0.12
NGC 2548	7.43	8.99	0.42	0.16
NGC 2632	5.73	8.78	0.10	0.10
NGC 2682	5.40	9.09	0.43	0.42
NGC 3114	6.61	8.53	0.55	0.06
NGC 3532	6.05	8.37	0.25	0.01
NGC 5822	5.46	8.21	0.76	0.05
NGC 6475	6.29	8.26	0.07	0.02
NGC 6633	5.91	8.33	0.06	0.05
NGC 7789	2.51	10.77	1.83	0.17
Hyades	5.75	8.72	0.19	0.02

the perigalactic and apogalactic distances R_p and R_a, respectively. Table 5 lists these three parameters, together with the present $|Z|$ values for the subset of 19 clusters. Since the mean $(R_a - R_p)$ difference for the 19 clusters is only 3 kpc, we confirm the suggestion of Carraro & Chiosi (1994a) that the radial abundance traced by the present day position of the clusters is probably reminiscent of the radial paleogradient. This also seems to be the case regarding the metallicity gradient along the Z direction. In fact, we have redetermined this gradient using both the current and computed maximum heights out of the plane for the cluster subsample. The results are illustrated in Fig. 4, wherein filled circles and open triangles represent current and maximum $|Z|$ values, respectively. A linear regression on the data gives $\partial[\mathrm{Fe/H}]/\partial|Z| = -0.38$ dex kpc^{-1} in the first case (practically the same as that obtained for the entire open cluster sample) and -0.20 dex kpc^{-1} in the second. Since the latter represents probably the most unfavourable situation to detect a gradient, we conclude that the original Z gradient cannot have been too seriously affected by the orbital motions of the clusters. It is seen from Fig. 4 that clusters more metal-rich than [Fe/H]~0.0 lie within 200 pc from the Galactic plane, with only two exceptions: NGC 2682 and NGC 5822. The remaining clusters have probably travelled far away from the plane and it is therefore likely that they have been born at higher $|Z|$ values than the metal-rich ones. If an important percentage of the observed metal-poor clusters had been born near the Galactic plane, they might have had initial W velocities in order to reach the calculated $|Z_{\max}|$ values, which is unlikely for objects with birthplaces confined to low $|Z|$ values.

4. SUMMARY AND CONCLUSIONS

In this paper we determine overall [Fe/H] abundances for 233 red giants in a sample of 63 open clusters with a wide range of ages. Mean cluster abundances are formed by averaging [Fe/H] over the stars in each cluster, which were previously confirmed to be members on the basis of their radial velocity, proper motion, and/or photometric information. This is probably the largest open cluster sample so far known with abundances derived on a homogeneous scale, using the same technique. This sample, which now includes young, intermediate-age, and old clusters, allows us to reinvestigate the existence and size of abundance gradients in the Galactic disk, as well as the form of the age–metallicity relationship. We confirm a radial abundance gradient whose magnitude (-0.07 dex kpc^{-1}) is similar to previously published values (e.g., Janes *et al.* 1988) and agrees with those predicted by models of chemical evolution of the Galaxy (e.g., Matteucci & Francois 1989). Concerning the AMR for the entire open cluster sample, we also confirm recent results, namely that at

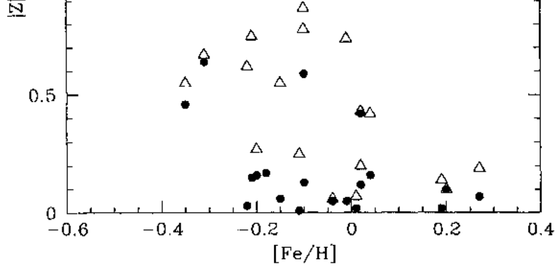

FIG. 4. Relationship between mean cluster abundances and height out of the Galactic plane for a subset of 19 open clusters. Filled circles and open triangles denote current and maximum $|Z|$ values. The data have been corrected for the R_{gc} dependence on metallicity.

any age there is a large scatter in metallicity, this scatter being particularly large for the youngest clusters, but we find no overall AMR. We also present clear evidence for a steep abundance gradient of -0.34 dex kpc^{-1}, perpendicular to the Galactic plane.

We have checked whether the radial and Z gradients derived from the present day positions of the clusters are good indicators of the original ones. To do this, we have computed orbital motions for a subsample of 19 open clusters with reasonably well-determined distances to the Sun, radial velocities, and proper motions. We have found that both the radial and Z gradients are probably reminiscent of the paleo-gradient ones.

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